Fermilab FERMILAB-Conf-03/113-T June 2003

CONCEPTUAL DESIGN OF LARGE-BORE SUPERCONDUCTING QUADRUPOLES WITH ACTIVE MAGNETIC SHIELDING FOR THE AHF

V.S. Kashikhin, G. Ambrosio, N. Andreev, S. Bhashyam, V.V. Kashikhin, T. Peterson, J. Tompkins, A.V. Zlobin, FNAL, Batavia, IL 60510, USA
A. Jason, J.P. Kelley, P. Walstrom, LANL, Los Alamos, NM 87544, USA

Abstract

The Advanced Hydrotest Facility, under study by LANL, uses large-bore superconducting quadrupole magnets. In the paper we discuss the conceptual design of such quadrupoles using active shielding. The magnets are specified to achieve gradients of up to 24 T/m with a 28-cm warm bore and to have 0.01% field quality. Concepts for quench protection and the magnet cryosystems are also briefly discussed to confirm the viability of the proposed design.

INTRODUCTION

The LANL Advanced Hydrotest Facility (AHF) [1] uses large-bore superconducting (SC) quadrupole magnets to image protons for radiography of fast events [2]. Since 12 imaging lines converge on the object to be radiographed [3], size limitations are an important consideration as is magnetic coupling between lines. The pre-conceptual magnetic analysis of warm yoke, cold iron-core and active shield versions was described in [4]. In this paper we investigate an active shielding version, a very promising approach for this application. The quadrupoles have two concentric windings connected in series and configured so that the outer winding effectively eliminates the outer fringing magnetic field. This design also eliminates problems connected with a warm or cold ferromagnetic core. The active shielding eliminates fringing fields and Lorentz forces between adjacent quadrupoles and reduces magnet weight and size.

Imaging lenses consist of several large-bore quadrupoles, which can either be wired in series using common current leads, or be powered separately. With the large number of magnets in the system, Hi-Tc current leads are preferred [5]. Cold masses might be cooled with forced-flow supercritical helium [6], or alternatively with pool-boiling helium [7]. The first approach is widely used in accelerators, the second one in MRI, SC spectrometers, etc. Brief discussion of both options, and a preliminary quench analysis is presented in this paper.

QUADRUPOLE DESIGN

Specification and Parameters

In order to meet the imaging system requirements for AHF, the focusing quadrupole magnets should satisfy the criteria presented in Table 1 [8]. In addition, due to the limited space, the magnets should generate a minimum fringe field outside to avoid interaction between magnets in the doublets and adjacent strings.

Table 1. Magnet parameters

Parameter	Small-bore	Large-bore
Operating gradient, T/m	24.15	13.18
Magnetic length, m	3.0	4.3
Reference radius R_{ref}, mm	113.4	241.3
Field quality at R_{ref}	$<10^{-4}$	$<10^{-4}$
Main coil inner radius, mm	170.0	322.0
Screen coil inner radius, mm	276.0	513.5
Iron screen inner radius, mm	345.0	595.0
Iron screen thickness, mm	10.0	10.0
Number of turns in the main coil	232	508
Number of turns in the shield coil	104	220
Coil area, cm^2	174.4	378.0
Operating current, kA	14.10	11.77
Quench gradient with NbTi, T/m	28.25	15.80
Quench current with NbTi, kA	16.49	14.11
Peak field in the coil, T	6.1	6.3
Inductance, mH/m	9.91	49.41
Nominal stored energy, kJ/m	985.4	3420.7
Max. field in the iron screen, T	0.4	0.2

Design Concept

The quadrupole design is based on the active shielding concept, in which the return flux from the main winding is suppressed using another winding carrying an opposite current. The cross-section of the large aperture quadrupole based on this concept is shown in Fig.1. This approach suppresses nearly all leakage flux and avoids the interaction between the cold mass and iron screen inherent in the warm iron yoke concept. It also avoids iron saturation effects, which cause field distortions.

A simple estimate shows that limiting the magnet current to reasonable values of 15-20 kA leads to several hundreds of turns in the windings for the given apertures and gradients. A traditional shell type coil with that number of turns would suffer from stress accumulation at the midplane and large random field harmonics coming from the variation of individual cable positions within the shells. Thus it was imperative to split the shells into a number of mechanically decoupled blocks, providing the stress management and individual positioning and support for each block.

In order to accomplish this task, winding into the support structure approach was chosen. The winding mandrel is a cylinder with rectangular slots machined in longitudinal direction. For easier stacking and prestressing inside the slots, the cable is wound in the "hard bend" way with the long edge tangential to the mandrel. In addition, to simplify the manufacturing, all slots in the mandrel are oriented radially. After the coil is wound and cured, the mandrel serves as the mechanical support structure for the coil.

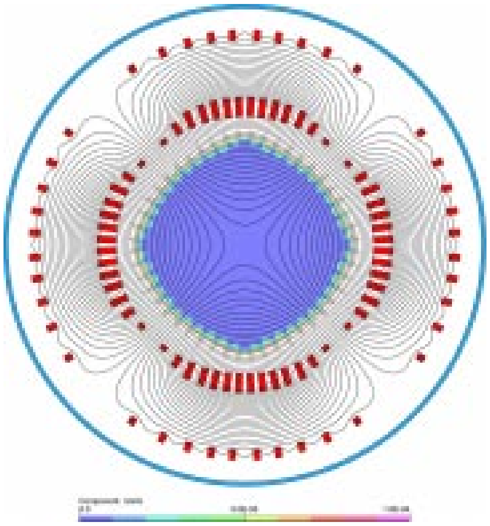

Fig. 1 Large-bore quadrupole field quality and flux lines

As opposed to the traditional shell-type magnet, the cable width in the proposed design concept does not drive the shell thickness and therefore the maximum gradient. It offers an opportunity of tuning the operating parameters by simply changing the number of turns in the blocks and neither the cable dimensions nor the number of layers. However, the cable width does drive the number of blocks and thus cost of the support structure, which should obviously be minimized. From this viewpoint, the maximum cable width acceptable for winding in the hard-bend direction should be chosen. Simple bending experiments demonstrated that a Rutherford type cable with 28 (1 mm in diameter) strands can be hard-bent around ~50-mm round mandrel without loss of stability. Given that the cable mechanical stability will be additionally enhanced by support from the mechanical structure during winding, the number of strands was fixed at 32.

Superconducting Cable

Both magnets are based on the same 32-strand cable with either NbTi or Nb_3Sn strands. The strand and cable parameters are summarized in Table 2. The higher critical current density and lower Cu:nonCu ratio in Nb_3Sn strands allows replacing significant amount of SC strands in Nb_3Sn cable with pure Cu strands while preserving the required field gradient.

Field Quality

Field quality in an air core magnet with large number of conductor blocks can be rather easily optimized to values of two orders of magnitude better than specified field harmonics 10^{-4}. Table 3 presents results of the optimized cross sections shown in Figures 1 and 2. Hence, the manufacturing accuracy will define the final field quality.

Table 2: Cable parameters

Parameter	NbTi	Nb_3Sn
Strand diameter, mm	1.000	
Number of strands	32	
Cable bare width, mm	16.214	
Cable bare thickness, mm	1.772	
Number of SC strands	32	8
Number of Cu strands	0	24
Copper to non-copper ratio	1.6	0.85
J_c(5T,4.2 K), A/mm^2	3000	-
J_c(12T,4.2 K), A/mm^2	-	2200

Table 3: Body field harmonics

n	b_n, 10^{-4}	
	Small-bore	**Large-bore**
6	-0.0012	-0.0002
10	0.0005	-0.0001
14	-0.0035	-0.0001
18	0.0005	0.0002

Random field harmonics were calculated as standard deviations among a large number of cases assuming +/-50 μm random block displacements from the nominal position. With these tolerances, the small bore will meet the field quality requirements for individual harmonics at the one σ level. However, due to the larger number of blocks, the large bore magnet with the same positioning tolerances will meet the field quality requirements at greater than the 3σ level or one can relax the tolerances to +/-140 μm to get the same probability.

A similar tolerance is placed on the end field harmonics. Three dimensional analysis and careful adjustment of the winding ends must be accomplished.

Quench Margin

The maximum field gradient was calculated for the quadrupoles made of NbTi and Nb_3Sn conductors with the properties shown in Table 2. Both the large and small quadrupoles using NbTi conductor achieve the maximum operating gradients with a 15-20% critical current margin. Using Nb_3Sn cable in these magnets increases the operating gradients by a factor of 1.5 with the same Ic margin.

Radiation losses in magnet coils will produce an extra heat load of 0.3–1.0 mJ/g. Fig. 2 shows the quench limit for NbTi and Nb_3Sn coils vs the magnet critical current margin. For operation at a heat deposition of 1.0 mJ/g, the critical current margin with NbTi coils has to be more than 25% while Nb_3Sn coils can operate with a margin of only 10%.

Quench Protection

Magnets will be protected with an active quench protection system based on the internal quench heaters as used in modern SC accelerators. Analysis shows that for a quench-detection time of ~50 ms and 50% coil volume quenched by the heaters, the coil maximum temperature does not exceed 300 K and maximum voltage between the coil and ground during a quench is less than 100 V.

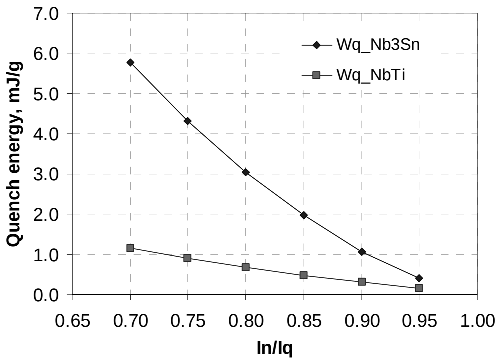

Fig. 2 Quench energy vs. coil critical current margin for NbTi and Nb_3Sn quadrupoles.

Cryosystem

The 12 intersecting lens-lines severely limit space for the cryo-distribution system. Also, unlike the simple end-to-end arrangement of magnets in RHIC or the Tevetron, the lens lines' arrangement does not lend itself to a simple flow through solution for cryogens as would be desired for a supercritical cooling approach. Initially, a pool-boiling approach was considered [5,6]. Supercritical flow is provided by a cryoplant located on the surface through a complex distribution system to JT valves on lens-line-magnet cryostats (Fig 3), nominally 50-m below grade. Flash and boiloff gas is returned to the cryoplant by a parallel route, possibly boosted by a cold compressor. Similar routing is used for thermal shield cooling (40-K, 4-atm helium), with some of this gas directed to Hi-Tc lead gas-cooled stages.

One potential problem with large heat loads in pool-boiling systems is the large volumetric flow rate required for removing vapor generated in tight spaces, particularly with density-gradient-driven flows (natural convection). Especially in non-vertical spaces of less than 1 mm, heat fluxes that can be removed by boiling and natural circulation start to drop off. Our extensive experience with pool-boiling cooled magnets in vertical test dewars may not be relevant, since heat loads there are typically minimal and local heat fluxes are very low. In spite of the geometric difficulties presented by the radial magnet arrangement, supercritical forced-flow cooling, which has been used successfully in long accelerator magnet strings such as RHIC, might have to be developed for the AHF system as an integral part of the magnet design.

Supercritical cooling is accomplished either with warm-compressor or cold-pump driven flow. High flow rates and recoolers are required to keep the helium temperature sufficiently below magnet-stability margins. Warm-compressor-driven flow cases were found to have prohibitive operating and capital costs [7]. With a single cold-pump driving the flow serially through the lens lines, 24 recoolers (two per line), and a pump-box, the purchase order cost of a supercritical-flow cryosystem (plant + distribution) is roughly 20% more ($5 M) than for a pool-boiling system, and consumes 23% (0.62 MW) more power. These differences are attributed to the additional equipment and associated heat load. Further studies are needed prior to finalizing the cooling approach.

Forced-flow liquid-helium cooling was not considered. This approach could lead to vapor trapping in magnets and jumpers, and density-wave type flow instabilities.

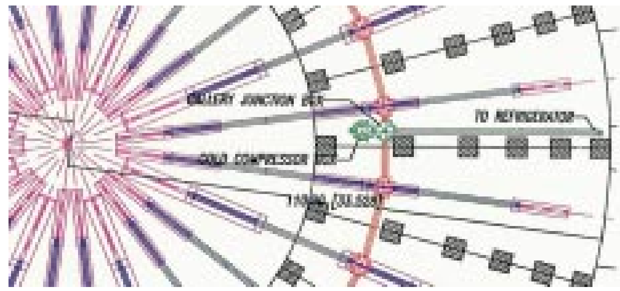

Fig. 3 Details of the AHF cryo-distribution system.

SUMMARY

Conceptual design of the AHF SC quadrupoles confirmed feasibility of the design based on the active shielding approach. The results, from this analysis, are:

- the specified field quality 10^{-4} can be achieved;
- quadrupole windings can be made from NbTi or Nb_3Sn superconductor;
- a proposed mechanical structure with adequate stress management;
- a quench protection system is viable;
- cryosystem concepts have been developed.

REFERENCES

[1] P.W. Lisowski and J.A. Paisner, "An Advanced Hydrotest Facility for the Stockpile Stewardship Program", Proc. of the 4th Int. Meeting on Nuc. App. of Accel. Tech., November 12-15, 2000, Washington D.C., p. 13.

[2] G.E. Hogan et al., "Proton Radigraphy", Proc. of the 1999 Part. Accel. Conf., 1999, p.579.

[3] C.T. Mottershead, J.D. Zumbro, "Magnetic Optics for Proton Radiography", Proc. of the 1997 Part. Accel. Conf., Vancouver, 1997, p.1397.

[4] N. Andreev et al., "Magnetic Design of Large-Bore SC Quadrupoles for the AHF", ASC 2002.

[5] J.P. Kelley, "The Impact of High Tc Leads on the AHF Lens Cryosystem of Firing Site 2," LANL Tech. Note, LA-UR-02-2692, Feb. 13, 2002.

[6] J.P. Kelley, "Cooling the FS-2 Lens System with Supercritical Helium – Cryosystem Considerations," LANL Tech. Note, LA-CP-02-516, Oct. 18, 2002.

[7] J.P. Kelley and G.T. Mulholland, "AHF Magnetic Lens Cryosystems," Adv. Cryo. Eng. Vol. 47, AIP Press, Melville, NY (2002), p. 60.

[8] P.W. Walstrom, "Magnetic Field Quality Specifications for the AHF Magnetic-Lens SC Quadrupoles", LANSCE-1 Tech. Note, LANSCE-1: 01-063, Aug. 23, 2001.